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October 27, 2009

Inertial Fusion Science and Applications
San Francisco, CA, United States
September 5, 2009 through September 10, 2009

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Features of a point design for Fast Ignition

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Abstract. Fast Ignition is an inertial fusion scheme in which fuel is first assembled and then heated to the ignition temperature with an external heating source. In this note we consider cone and shell implosions where the energy supplied by short pulse lasers is transported to the fuel by electrons. We describe possible failure modes for this scheme and how to overcome them. In particular, we describe two sources of cone tip failure, an axis jet driven from the compressed fuel mass and hard photon preheat leaking through the implosion shell, and laser prepulse that can change the position of laser absorption and the angular distribution of the emitted electrons.

1. Introduction

The energy required to ignite fuel in the Fast Ignition scheme[1] depends on both the assembled fuel density and the coupling efficiency. We require that the ignition region has column density about 0.6 g/cm^2 in order trap alpha particles during the heating phase and that this ignition region is embedded in a fuel with total column density at least 1.5 gm/cm^2 so that the fuel has time to climb in temperature from the 10 keV of ignition to the 30+ keV of robust burn. For fixed column density and ignition temperature, the ignition energy scales like ρ^{-2} . We can produce this high fuel density by imploding the fuel.

This leaves us with the problem of how to efficiently couple the short pulse laser energy to the fuel. We use a cone embedded in the implosion system[2]to provide open access for the short pulse laser to reach the fuel. The required implosion can have deleterious side effects on the coupling efficiency. First, the stagnated fuel itself can produce a high pressure jet, that pushes back the cone tip and the critical surface facing the short pulse laser. This effect is discussed in section 2. The interaction of the laser driving the implosion either with the hohlraum wall or with the ablator material can produce hard photons that penetrate the imploding shell and ablate some of the cone material. This cone material can mix with fuel and inhibit ignition or impede the stagnation. This xray preheat problem is discussed in section 3. Another preheat problem is caused by the prepulse of the ignition laser. Lasers using OPCPA typically have 10^{-5} - 10^{-4} of the incident energy appearing 1-3 nanoseconds before the main pulse. The effect of this prepulse in the cone is discussed in section 4. Section 5 summarizes the work.

2. Cone tip survival and electron transport efficiency

The transport efficiency is a strong function of the distance between the electron source and the ignition region. LSP[3] was used to model the electron transport between sources and ignition regions for two electron density distributions abstracted from hydrodynamic simulations. The electron source was abstracted from explicit PIC simulations driven at $I\lambda^2 = 5 \cdot 10^{19} \text{ W cm}^{-2}\mu\text{m}^2$. The simulations resulted in an electron distribution with the median energy 4.4 MeV and half-width-half-max of the angular distribution 50° . Table 1 summarizes the results for the nominal electron distributions and those with half the opening angle. The simulations based on the smaller source to fuel region distance had substantially greater coupling efficiency.

Coupled energy	30 micron separation	110-130 micron separation
Nominal angle	20%	4%
Half angle	50%	18%

Table I. Coupling efficiency as function source to fuel separation and source opening angle

What causes the large standoff between the fuel and the electron source in most simulations when we can initialize the cone-center of implosion distance arbitrarily? Simulations of this system show an axis jet that flows from the converged fuel to the cone tip. The pressure in this jet is comparable to the stagnation pressure of the compressed fuel and adequate to send a strong shock through the cone tip. When the shock breaks out from the back of the cone, the ensuing rarefaction can drive the critical surface hundreds of microns away from the compressed fuel. This jet is generated because the stagnation pressure of the fuel is balanced by the ram pressure of the incoming flows in all directions except in the cone direction.

Can we abate this jet by interposing additional material between the compressed core and the cone tip? We use a simple system to give insight into the physics. The initial state is a 1D slab composed of 60 microns of 500 g/cm^3 hydrogen touching 70 microns of 10 g/cm^3 hydrogen. Naively, we would expect that the side with the tamping would show slower shock propagation than the untamped side. The simulation showed that there was little difference between the tamped and untamped sides. This occurs because the adiabatic expansion of the dense plasma is limited by its internal sound speed, not the relatively low-density tamper.

The jet has time to impact the cone tip because the fuel comes to high pressure before enough column density has assembled. A possible solution is to assemble the part of fuel near the cone early so that when the shock has propagated through this fuel the entire fuel has assembled. That is, we can win the race with the reflected shock. Figure 1 shows an example of this strategy. Two capsules were imploded around an immovable cone. One capsule was symmetric, while the other had the cone side leading the opposite by 100 microns when the average radius was 300 microns. The density distributions of both capsules at stagnation are similar. However, the symmetric capsule generates a high pressure as its flow stagnates on the cone. No such feature exists for the asymmetric one. The asymmetric design generates pressure more than an order of magnitude smaller at this location. That pressure is due to the Prandtl-Meyer flow splashing on the symmetry axis—not the jet from the core.

3. Hard photon preheat and cone tip expansion

The long pulse laser driving the fuel assembly produces electron temperatures of several keV in the blowoff of the hohlraum wall for indirect drive or in the capsule corona for direct drive. These heated electrons can produce multi-keV photons by bremsstrahlung, free-bound radiation or line radiation. These hard photons can, in turn, penetrate the capsule and heat the high-Z cone. The high-Z material can then expand, impede the implosion and possibly mix with the fuel. When the mass fraction of Au in DT reaches 0.006, the required ignition energy deposited in the fuel triples. For our indirectly driven designs, we estimate the amount of cone blowoff by using the photon spectra calculated in integrated hohlraum+capsules simulations, determining the spectra that leak through the capsule shell, then driving a gold sphere with these leakage photons and determining how far the surface of the sphere expanded under various conditions. There are two ways we can reduce the cone blowoff: introduce seeding in the ablator in order to attenuate these photons. For example we graded the doping

of iodine(maximum 1 per 15 $\text{CH}_{1.3}$) over the nominal payload for a capsule driven with a peak radiation temperature of 200 eV. The doping must be graded as to avoid density gradients that can increase the growth of the Rayleigh-Taylor instability. This effectively doubles the payload mass, and lowers the peak compression. Or we can cover the cone with a low Z(carbon or beryllium) tamper; here 10 microns of density 3.47 carbon. Table II summarizes the results.

shield	Tamper(micron)	Au excursion(micron)
yes	10	10
yes	0	130
no	10	33
no	0	180

Table II. Au expansion as function of tamper and shield

Other implosion scenarios are possible. The design above used a conventional pulse shape, where 4 shocks are timed to coalesce just across the gas/inner payload interface. These pulseshapes come to peak power before the shell has moved far. They efficiently couple the radiation to the capsule because the capsule still has large surface area at this time. This is also the time of peak laser intensity and hard photon production Unfortunately, this is before the shell has thickened because of convergence effects. The attenuation of the preheat photons is the same as it is for plane slab. We have also considered another pulse shape that was originally designed to produce a completely isochoric fuel assembly[4]. In that pulseshape, peak intensity is delayed until the capsule converged more. The efficiency of radiation absorption is reduced, but the column density of the dopant has increased. Hence a given mass of dopant attenuates the hard photons an order of magnitude more efficiently than the conventional design and the mass that was taken by the doped ablator can be returned to the ablator or real payload. This scheme has been used in integrated calculations[5]. Another possibility is to replace the high-Z cone with a high density carbon one. The opacity of carbon for these hard photons is sufficiently small that it is not heated above the boiling point. There will be increased hydrodynamic losses to the cone, however.

Directly driven capsules can also suffer from this cone ablation. A capsule driven by 1 MJ of 354 nm light at peak intensity $1.4 \cdot 10^{15} \text{ W/cm}^2$ drove a gold expansion of 65 microns. This expansion wasn't seen in high gain capsules driven at $3 \cdot 10^{14} \text{ W/cm}^2$. An integrated 2-D simulation of recent Omega experiments saw the cone expand a few tens of microns.

4. Reducing the prepulse from the shortpulse laser.

Shortpulse lasers often have prepulses arriving 1-3 nanoseconds before the main pulse and carrying 10^{-3} - 10^{-5} of the total energy. These 10's of millijoule prepulses produce plasmas extending over 100 microns. There is anecdotal evidence from existing experiments and simulations using cone targets[6] that these preplasmas significantly move the location of the laser absorption upstream from the cone tip and broaden the angular distribution. Calculations without prepulse show the source of hot electrons at the cone tip with a 40° to 50° half angle[7]. Baton et.al., inferred a reduction in forward going electrons of more than an order of magnitude when an approximately 10 mJ prepulse was injected into a cone compared a frequency doubled pulse without prepulse. Simulations suggested that the electrons were driven sideways into the cone walls, not forward. Our understanding of this situation is incomplete, but the trend is discouraging. Full scale Fast Ignition may require short pulse laser energies of order 100kJ, leading to prepulses in the 1-10J region. Developing techniques to reduce these prepulses is a sensible precaution.

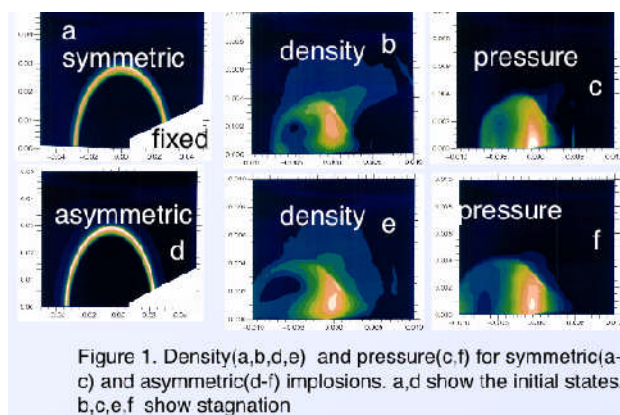
Laser based schemes that can reduce this prepulse include double OPCPA[8] and intensity dependent polarization rotation[9]. Implementing such schemes would be the preferred way to solve this problem. However, such implementations may be difficult for a given laser. As an alternative we looked for plasma based solutions. Plasma mirrors in which light with intensity above 10^{15} forms a plasma that then specularly reflects light have been demonstrated in short pulse laser experiments. The low intensity prepulse does not form a plasma and therefore does not reflect the light. Unfortunately,

the reflection efficiency at high intensity is only 50% and after about 1 ps the surface roughens and the reflection is no longer specular.

We suggest using inverse Bremsstrahlung absorption to selectively absorb the prepulse while allowing the main pulse through. For example, consider a 3 ns 1 J prepulse of 1 micron light incident on a 4 eV hydrogen plasma of density 10^{-5}g/cm^3 1.5 cm long followed by a 10 ps 100kJ pulse. The plasma is preheated so that there are sufficient electrons for efficient inverse Bremsstrahlung. The prepulse intensity was reduced by at least 5 orders of magnitude(the code cutoff), while only 4.5% of the high intensity pulse was absorbed because this plasma was sufficiently heated(1keV-100 keV) to turn off the inverse Bremsstrahlung. At an electron density of $5 \cdot 10^{18}/\text{cm}^3$ and power 10^{16}W , this system is well above the threshold for relativistic self-focusing. Further work is required on the focusing and laser-plasma instability properties of this system.

5. Summary

We have described three detrimental issues for Fast Ignition and novel approaches to deal with them. Jets launched from the compressed fuel can destroy the cone tip and further separate the critical surface from the fuel. Asymmetric implosions can delay this jet formation. Hard photons made in the hot coronal plasmas can preheat the high-Z cone used to guide the implosion. The high-Z blowoff can mix with the fuel or retard the implosion. Mitigation measures are adding dopants to the ablator, tamping the cone with low-Z, changing the drive pulse shape or using a diamond cone. Laser prepulse can dramatically alter the shortpulse laser coupling to the fuel. Using a low density hydrogen is one way to eliminate this prepulse. Prepared by LLNL under Contract DE-AC52-07NA27344.



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